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Research Article
Spring Wheat-field Pea Rotation with Tillage Systems and Straw Retention Improves Soil Water Utilization and Reduces Carbon Emission

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Abstract

Background and Objective: Soil tillage and crop rotation are used to increase crop production and resource use efficiency worldwide. This study aimed to quantify soil respiration (Rs), Water Use Efficiency (WUE) and grain yield in spring wheat-field pea rotation in a rain-fed semi-arid environment. **Methodology:** The tillage practices included; conventional tillage with straw removed (T), no-till with straw removed (NT), no-till with straw retention on the soil surface (NTS) and conventional tillage with straw incorporated (TS), administered in a randomized block design with three replicates. Soil respiration was monitored in the 2016 cropping season using LI-8100 system (LI-COR, USA). **Results:** Grain yield and WUE in spring wheat were approximately 26.43 and 37.86% higher, respectively in NTS compared with T. In a less magnitude, TS also significantly increased grain yield and water use efficiency by ≈15.96 and 26.82%, respectively, compared with T and NT treatments. In field pea plots, NTS and NT increased grain yield and WUE by ≈35.60 and 26.35% compared with T treatments. The NTS had carbon emission of 436.05 kg ha^{-1} in spring wheat and 288.45 kg ha^{-1} in field pea, representing 31.89 and 25.88% less carbon emitted than T treatment during the growing season. The NT decreased carbon emission, but the effect was lesser relative to NTS. **Conclusion:** The findings of the present study show that spring wheat-field pea rotation with tillage removal coupled with straw retention can be used to increase grain production and reduce carbon emission in semi-arid areas.

Key words: Crop production, crop rotation, no tillage, soil moisture, soil respiration

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Greenhouse gas emission and climate change are important issues in agriculture because agriculture is a major contributor to the build-up of greenhouse gases in the atmosphere. The main drivers of change are carbon dioxide (CO_2) emissions, which represents about 77% mainly from fossil fuel use and land-use change[1]. Carbon emission is the most important factor threatening ecological sustainability[2]. Farm lands are a major carbon source of GHG, accounting for 14% of the anthropogenic emissions globally[3]. However, with population continuously increasing, the challenge is to increase food production while reducing environmental costs. This has been a challenge in highly-populated countries such as China and India[4]. Therefore, the development of low-carbon agriculture systems to store as much carbon as possible in soils is considered an urgent measure in crop production[5].

Among mitigation measures, conservation farming systems that include reduced tillage or No Tillage (NT) vis-à-vis Conventional Tillage (CT) is promoted as a viable option to ensure sustainable food production and maintain environmental integrity[6]. Reduced tillage or no-till has been increasingly used worldwide due to their environmental advantages and lower labor inputs[7] over conventional systems. Most studies have declared that no-till decreases soil disturbance[8] and lowers CO_2 emission from the soil[9]. In conservation farming practices, crop residue management has a crucial impact on the C and N cycles and thus has the potential to enhance the sequestration of C in soils. Straw retention under a shallow non-inversion tillage system has been reported to significantly increase the soil carbon content in the 0-30 cm soil layer[10]. Despite numerous investigations, the impact of tillage on soil CO_2 emissions has largely been inconsistent. Several studies have reported that CO_2 emissions were decreased, unchanged or increased under no or minimum tillage[11-13].

The research of sustainable tillage technologies carried out in different countries shows different influence of the technologies on the physico-mechanical properties of soil and carbon emissions. The effects of tillage technologies on carbon emissions from Loessial soil in semi-arid rain-fed areas are insufficiently investigated and poorly substantiated on research. This study hypothesized that non-ploughed based system allows the increase of crop yields with improved water use efficiency, while reducing carbon emissions from farming. Here, we determined (1) The responses of grain yield, evapotranspiration and carbon emission of spring wheat-field pea rotation to different tillage and straw retention options and (2) Determine carbon emission per unit of water and the carbon emission efficiency of spring wheat-field pea rotation under different tillage and straw retention options in the Western Loess Plateau.

MATERIALS AND METHODS

Site description: A field experiment was carried out under rain-fed conditions in 2016 at Dingxi Experimental Station of Gansu Agricultural University, China (35°28 N, 104°44 E, 1971 m a.s.l.). The soil is a Loessial soil of sandy-loam with low fertility, classified as *Calcaric cambisols*[14]. This soil type has a sandy-loam texture and relatively low fertility with pH of ≈8.3, Soil Organic Carbon (SOC) $\leq$7.65 g kg^{-1} and Olsen-P $\leq$13 mg kg^{-1}. This soil type is primarily used for cropping and is the dominant soil in the district. Long-term (1981-2010) annual mean precipitation is 391 mm, with about 54% occurring between July and September. Daily maximum temperatures can rise to 38°C in July, while minimum temperatures usually drop to -22°C in January. Annual cumulative temperatures >10 are 2240°C and annual radiation is 5930 MJ m^{-2} with 2477 h of sunshine. The experimental site has a long history of continuous cropping using conventional tillage practices. The experiment has been maintained without any alterations since 2001 prior to this flax experiment (*Linum usitatissimum* L.) were cropped. In-crop season rainfall recorded at the site during the course of the experiment was 239 mm.

Experimental design: Cropping during the experiment included a spring wheat (cv. Dingxi 35) and field pea (cv. Yannong) double sequence rotation (referred to as W→P→W and P→W→P sequence) with both phases present in each year. The experiment utilized four tillage systems which were: Conventional tillage with straw removed (T), no-till with straw removed (NT), no-till with straw retention on the soil surface (NTS) and conventional tillage with straw incorporated (TS). Conventional tillage was the local farming practice which included moldboard ploughing immediately after harvesting the previous crop (July-August), with a second ploughing prior to sowing in spring (March-April), all to a depth of 10-20 cm. Harrowing was carried out prior to sowing in spring. In T plots, all plant residues was removed before ploughing, whereas in the TS plots, all plant material from the previous crop was returned to the original plots immediately after threshing and then incorporated into the soil with ploughing. In NT plots, all the plant material was removed at harvest, whereas in

NTS plots, all the plant material from the previous crop was returned to the original plots after threshing and spread evenly on the soil surface. All the crops and treatments were sown with the same no-till seeder. Treatments were arranged in a randomized complete block design with three replicates. Each plot was 4 m wide×17 m long in block 1, 21 and 20 m long in blocks 2 and 3.

Spring wheat was sown in mid-March at a rate of 187.5 kg ha^{-1} with a row spacing of 20 cm and harvested in late July, to early August. Field pea was sown in early April, at a rate of 180 kg ha^{-1} with a row spacing of 24 cm and harvested in early July, each year. Nitrogen and phosphorus were applied at 105 kg N ha^{-1} as urea (46% N) and 45.9 kg P ha^{-1} as calcium superphosphate (6.1% P), respectively for spring wheat and 20 kg N ha^{-1} and 45.9 kg P ha^{-1} for field pea. All the fertilizer was applied at sowing with the no-till seeder.

Measurement and calculation

Grain yield: Plots were harvested by hand using sickles to a height of 5 cm above the ground and by discarding the outer edges (0.5 m) from each plot. Grain yield was determined on a dry-weight basis by oven-drying the grain at 105°C for 45 min and then to constant weight at 85°C.

Soil water use characteristics

Soil water content: Soil water content (%, w/w) was measured at sowing and harvest stages at six depth intervals as follows: 0-5, 5-10, 10-30, 30-50, 50-80 and 80-110 cm, respectively. The soil water content in the 0-5 and 5-10 cm depth intervals was measured using the oven-drying method described by Jia *et al.*[15]. Gravimetric water content (0-5 and 5-10 cm) was multiplied by soil bulk density to obtain the volumetric water content. Trime-Pico IPH (Precise Soil Moisture Measurement, IMKO Micromodultechnik GmbH, Ettlingen, Germany) was used to measure volumetric soil water content in 10-110 cm depths. Soil water storage was extrapolated from the volumetric soil water content by multiplying it by the layer depth.

Evapotranspiration (ET): Evapotranspiration was determined using the equation of Wang *et al.*[16]:

$$ET = P - \Delta W \quad (1)$$

where, ET is total evapotranspiration, P is total precipitation for the growing season and ΔW is the difference between soil water storage at sowing and harvest, respectively.

Water Use Efficiency (WUE): Water Use Efficiency (WUE) was determined by using Eq. 2 described by Wang *et al.*[16]:

$$WUE = \frac{Y}{ET} \quad (2)$$

where, WUE is water use efficiency, Y is grain yield (kg ha^{-1}) and ET is total evapotranspiration over the entire growing season (mm). All parameters are expressed in mm. Previous studies conducted at the study site reported no significant runoff or drainage during the growing season[17].

Carbon emissions characteristics

Seasonal variations of soil respiration (Rs): Soil respiration was measured with a LI-8100 system (LI-COR Inc, Lincoln, NE, USA) connected with a diameter of 20 cm proprietary respiration chamber. Three PVC chambers with the same size as the respiration chamber was placed on the soil surface and then pushed to a depth of 50 mm. These chambers were installed permanently throughout the measuring period. Before measuring, all crop residues and other litters on soil surface were removed. Measurements were made at the three spots where the PVC chambers were randomly placed in each plot, three values were recorded for each spots within 180 sec and the average value was used for each plot. For each measurement event, gas sampling was performed between 08:00-12:00 h, based on the guidelines of Alves *et al.*[18], so as to capture diurnal patterns of high microbial activity. The soil respiration was determined during March-September, because that period represents the main cropping seasons under rainfed agriculture in North Western China. It was assumed that soil respiration during the dry seasons would be very low and comparable across treatments due to a possible low microbial activity in dry soils[19].

Soil temperature: Synchronous with gas sampling, soil temperature at 5, 10 and 15 cm were determined using a geothermometer inserted into each plot in the area near the chamber.

Carbon Emission (CE): Carbon emission (kg ha^{-1}) was estimated based on soil respiration (Rs) using the following equation described by Zhang *et al.*[20]:

$$CE = \sum \left[\frac{Rs_{(i+1)} + Rs_i}{2} \left[t_{(i+1)} - t_i \right] \times \frac{12}{44} \right] \times 24 \times 10 \quad (3)$$

where, Rs is soil respiration (μmol CO_2 m^{-2} sec^{-1}) measured at 14 days intervals during the sampling period, i+1 and i are the previous and the current measuring date, respectively and t was days after sowing.

Carbon Emission Efficiency (CEE): In order to quantify the relationship between grain yield and carbon emissions, we use the term "Carbon Emission Efficiency (CEE)" which was expressed as:

$$\text{CEE} = \frac{\text{GY}}{\text{CE}} \tag{4}$$

where, GY and CE are grain yield (kg ha^{-1}) and carbon emission (kg ha^{-1}), respectively.

Carbon emission per unit of water (WUE_{CE}): The term "Carbon emission per unit of water (kg ha^{-1} mm^{-1})" was used to describe the magnitude of carbon emission (kg ha^{-1}) associated with per unit ET (mm) and the equation is calculated as follows:

$$\text{WUE}_{\text{CE}} = \frac{\text{CE}}{\text{ET}} \tag{5}$$

where, CE is the carbon emissions (kg ha^{-1}) and ET is the evapotranspiration (mm).

Statistical analysis: The data were analyzed using Statistical Analysis Software (SPSS software, 22.0, SPSS Institute Ltd., USA) and treatment effects were determined using the Duncan's multiple-range test. Significances were declared at the probability level of 0.05.

RESULTS

Yield performance: Overall, there were significant differences in grain yield depending on the treatment, which was observed both crops (Fig. 1). Grain yield in no-till with straw retention on the soil surface (NTS) and conventional tillage with straw incorporated (TS) plots was 1823 and 1676 kg ha^{-1} (≈26.43 and 17.28% higher than conventional tillage with straw removed (T) and no-till with straw removed (NT), respectively) in spring wheat plots. In field pea plots, no-till treatments (NTS and NT) significantly increased grain yield by 32.99 and 7.30%, respectively compared with conventional tillage with straw incorporated.

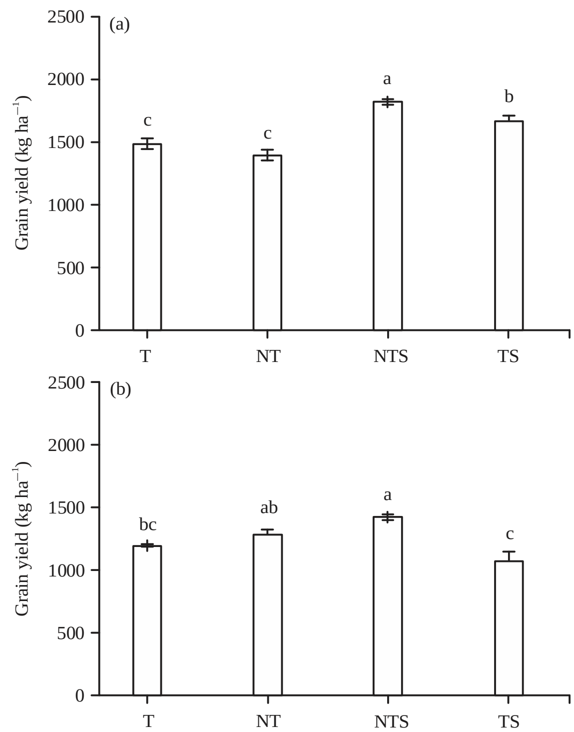

Fig. 1(a-b): Grain yield in (a) Spring wheat and (b) Field pea under different tillage treatment. Vertical bars represent the standard error. Means±SE from three replicates

Soil water characteristics

Soil moisture: No-till with straw retention (NTS) and conventional tillage with straw incorporated (TS) significantly increased soil water storage before sowing and at maturity in spring wheat (Table 1). However, there was no significant difference among treatments in soil water storage before sowing and maturity in field pea. Conventional tillage with straw removed (T) significantly decreased soil water storage by 16.06 and 10.68% at sowing and harvesting in spring wheat. The increased soil moisture was largely because straw covering on the soil surface decreased soil evaporation under the limited water condition.

Evapotranspiration: The ET (mm) of the spring wheat in the no tillage with straw retention on the soil surface (NTS) system was decreased ($p<0.05$) by 11.96 and 11.62% in spring wheat and field pea compared with control (Table 1). Meanwhile, significant differences were not observed among conventional tillage with straw removed (T), no tillage with straw removed (NT) and conventional tillage with straw incorporated (TS) treatments in spring wheat plots. In the field pea plots, there was no significant difference among

Table 1: Soil water storage (mm) before sowing and after harvest, evapotranspiration (ET) and Water Use Efficiency (WUE) in Spring Wheat (SW) and Field Pea (FP) under different tillage treatment

	Before sowing		After harvest		Evapotranspiration (mm)		WUE (kg ha^{-1} mm^{-1})	
Treatments	SW	FP	SW	FP	SW	FP	SW	FP
T	331^{c}	396^{a}	297^{c}	330^{a}	206^{a}	174^{a}	7.24^{c}	6.91^{b}
NT	346^{bc}	387^{a}	303^{bc}	329^{a}	196^{ab}	180^{a}	7.14^{c}	7.12^{b}
NTS	384^{a}	381^{a}	328^{a}	317^{a}	184^{b}	175^{a}	9.92^{a}	8.18^{a}
TS	368^{ab}	371^{a}	313^{b}	323^{a}	184^{b}	191^{a}	9.12^{b}	5.64^{c}

Values with different letters within a column are significantly different at p<0.05 and means comparison was done using Duncan's multiple range test (p<0.05)

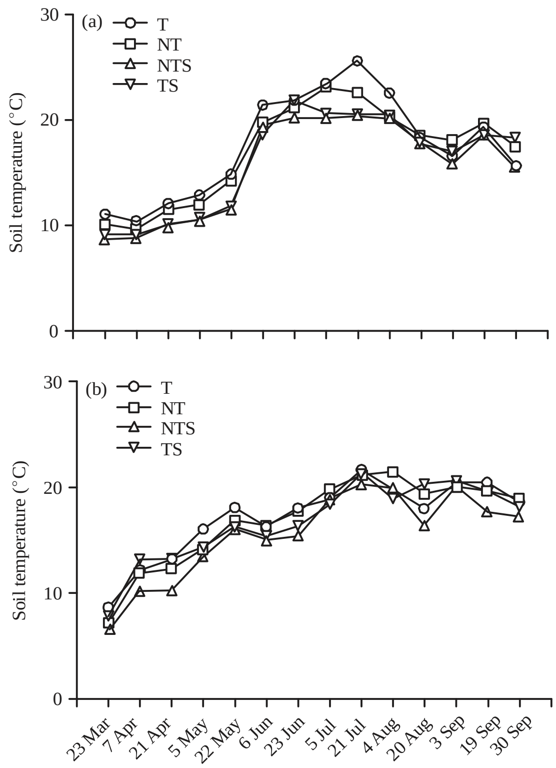

Fig. 2(a-b): Average soil temperature in (a) Spring wheat and (b) Field pea at 0-15 cm under different tillage treatments

the treatments evaluated (Table 1). However, NTS had non-significantly higher ET compared with the other treatments.

Water use efficiency: No-till with straw retention on the soil surface (NTS) and conventional tillage with straw incorporated (TS) had a consistent influence on WUE either in the spring wheat field or field pea plots (Table 1). In the spring wheat plots, no tillage in combination with straw retention (NTS) improved water use efficiency by 38.81 and 36.91%, in comparison to conventional tillage with straw removed (CT) and no tillage with straw removed (NT), respectively. At a lower magnitude, conventional tillage with straw incorporated (TS) significantly increased water use efficiency by 27.69 and 25.94% compared with conventional tillage with straw removed (CT) and no tillage with straw removed (NT), respectively. Similarly, in field pea plots, NTS significantly increased water use efficiency by 14.98, 18.52 and 45.06% relative to NT, T and TS, respectively. In addition, NT and T increased water use efficiency by ≈24.27% compared with TS.

Carbon emission characteristics

Seasonal variations of soil respiration and carbon emission: Seasonal soil respiration (Rs) peaked in May and July. This was in accordance with the temperature changes (Fig. 2). The seasonal Rs presented a double peaks curve with Rs peaking both on two occasions during the sampling period (Fig. 3). The major seasonal Rs of spring wheat peaked on 5 and 21 July, (Fig. 3a). Similarly, the major seasonal Rs of field pea occurred on 5 July and 4 August (Fig. 3b). On average, no-till treatments (i.e., NTS and NT) significantly reduced seasonal soil respiration (Rs) in both spring wheat and field pea plots (Table 2). No-till coupled with straw retention on the soil surface (i.e., the NTS system) and no-till with residue removed had the least averaged Rs of 2.71 and 3.09 μmol CO_2 m^{-2} sec^{-1} in spring wheat plots, representing a decreased of 35.56 and 18.75%, respectively, compared with conventional tillage with straw removed (T) plots. Similar trend was observed in field pea plots. No-till treatments (i.e., NTS and NT), consequently, decreased carbon emissions (CE) significantly compared to conventional tillage with straw removed (T) (Table 2). Carbon emission in NTS and NT were 31.90 and 17.05% lower compared to T in spring wheat plots. Similarly, in field pea plots, carbon emission in NTS and NT were 25.89 and 18.13% lower versus T.

Carbon emission efficiency: Carbon emission efficiency determines how much grain yield was associated with per unit of carbon emitted. The NTS significantly increased Carbon Emission Efficiency (CEE) compared to T, NT and TS in both spring wheat and field pea (Table 2). The NTS practices improved CEE in both spring wheat and field pea by ≈44.08% compared with the other treatments.

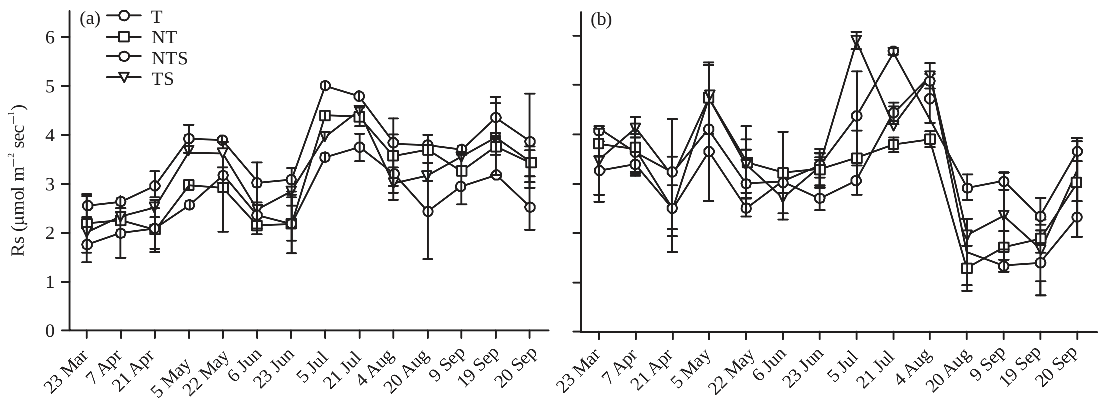

Fig. 3(a-b): Seasonal soil respiration (Rs) in (a) Spring wheat and (b) Field pea under different tillage treatment. Vertical bars represent the standard error. Mean±SE from three replicates

Table 2: Carbon Emission (CE), averaged soil respiration (Rs), Carbon Emission Efficiency (CEE) and carbon emission per unit of water (WUE_{CE}) of Spring Wheat (SW) and Field Pea (FP) under different tillage treatmen

	CE (kg ha^{-1})		Rs (μmol m^{-2} sec^{-1})		CEE (kg kg^{-1})		WUE_{CE} (kg ha^{-1} mm^{-1})	
Treatments	SW	FP	SW	FP	SW	FP	SW	FP
T	575^{a}	363^{a}	3.67^{a}	2.38^{a}	2.60^{c}	3.31^{c}	2.80^{ab}	2.10^{ab}
NT	491^{bc}	307^{b}	3.09^{bc}	2.06^{b}	2.84^{bc}	4.18^{b}	2.51^{bc}	1.73^{ab}
NTS	436^{c}	288^{b}	2.71^{c}	1.88^{c}	4.21^{a}	4.96^{a}	2.37^{c}	1.65^{b}
TS	527^{ab}	353^{a}	3.22^{b}	2.30^{a}	3.18$_{b}$	3.03^{c}	2.87^{a}	1.85^{ab}

Values with different letters within a column are significantly different at p<0.05 and means comparison was done using Duncan's multiple range test (p<0.05)

Carbon emission per unit of water: Conventional tillage with straw incorporated (TS) and conventional tillage with straw removed (T) had the greatest carbon emission per unit of water used (WUE_{CE}) compared with no-till with straw retention (NTS) (Table 2). The adoption of NTS (2.37 kg ha^{-1} mm^{-1} in spring wheat and 1.65 kg ha^{-1} mm^{-1} in field pea) reduced carbon emission per unit of water by 21.24 and 27.16%, respectively over T.

DISCUSSION

The increase awareness of food security and climate change is driving the interest of policy-makers, researchers and the society as a whole, to explore how farming systems can be improved to produce high-quality and affordable food in sufficient quantities, while minimizing potentially negative impacts on the environment[21,22]. The present study demonstrates that no-till with residue retention on the soil surface significantly increased grain yield compared to conventional tillage with residue removed (T). The increased yields under no-tillage were mainly ascribed to non-disturbance and retention of crop residues at the surface resulting in increased soil water availability. The positive aspects of surface retention of crop residues are a reduction in evaporation losses from soil and increase in water conservation[17]. As reported by Yeboah *et al.*[23], non-ploughed based farming system and retaining residue in rain-fed conditions increased and stabilize crop yields. These findings suggest that no-till offer promise as a means to improve crop performance and yield of spring wheat and field pea under semi-arid conditions.

Agriculture in rainfed dry areas is often challenged by low availability of water which is threatening agricultural sustainability in those regions[24]. The challenge is serious in many arid and semiarid regions of the world, such as Northwest China[25]. A key strategy is to adopt improved farming practices in crop production that could increase water use efficiency and possibly reduce water consumption. In the present study, no-till with residue retention (NTS) and conventional tillage with residue incorporation (TS) was shown to increase soil water availability, water use efficiency albeit reducing evapotranspiration, particularly in the spring wheat plots. A combination of crop residue retention with reduced tillage or no-till management has been found to increase water infiltration, reduce water loss by restraining evaporation and evapotranspiration[26] and improve crop water use efficiency[27]. Application of no-till practices could therefore, be used to store more rainfall in soil and increase water use efficiency in dryland areas.

A small change of soil respiration can have a large impact on CO_2 concentration in the atmosphere[28]. Hence, soil respiration constitute a crucial part of C cycle in agro-ecosystems. Seasonal dynamics of GHG emissions in rain-fed spring wheat and field pea followed a similar trend to soil temperature and dry matter accumulation, with a maximum exhibited in July. The high Rs during summer were attributed to high soil temperatures and the greatest dry matter accumulation[29]. In this study, no-till with residue retention (NTS) and no-till with residue removed (NT) significantly reduced seasonal Rs and carbon emission compared to conventional tillage with residue removed (T) and this was consistent in both crops studied. Conservation tillage, such as no tillage or reduced tillage decreases soil disturbance, inhibits soil microbial activities and lowers carbon emission from the soil[30]. Moreover, reduced tillage with residue retention can further reduce the emission of CO_2 from the soil[31]. In contrast, a study by Ussiri and Lal[11] found, no-tillage exhibited larger CO_2 emissions and they attributed this to the decomposition of old weathered residues.

Basically, an increase in Carbon Emission Efficiency (CEE) could be achieved through either an increase in grain yield or a decrease in soil respiration or both. The no-till with residue retention (NTS) and no-till with residue removed (NT) significantly improved the CEE by increasing the grain yield and decreasing carbon emission. The increase in grain yield and reduction in carbon emission may be related to the reduced soil temperature which may have inhibited microbial activity leading to reduction in root respiration. Increased in CO_2 emission could be attributed to rapid decomposition of organic materials as a result of enhanced microbial activities[32]. Thus, the NTS and NT soil management strategy is a promising option for the development of sustainable agriculture in semi-arid areas.

CONCLUSION

The conservation tillage system performed successfully in North Western China, a typical rain-fed semi-arid agricultural region. Application of no-till with residue retention (NTS) improved soil conditions by increasing soil moisture and reducing soil temperature and evapotranspiration to significantly greater extent than the other treatments tested. This translated into higher water use efficiency and therefore grain yield in that treatment. The no-till with residue retention (NTS) and no-till with residue removed (NT) showed lower soil respiration and carbon emission, but the effect of NTS was consistently greater. An added feature of the NTS treatment is that carbon emission efficiency was increased in both crops compared to T plots. It is conclude that, spring wheat-field pea rotation with no-till with residue retention (NTS) can be used to effectively lower carbon emission and to enhance carbon emission efficiency while improving grain yield and water use efficiency under dryland cropping systems.

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